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Effects of Hydraulic Model on Gas Productivity and Geomechanical Stability During Methane Hydrate Production by Depressurization

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Abstract. The permeability of hydrate-bearing sediments is a key parameter in assessing the methane gas productivity as it generally varies with the hydrate saturation. Numerous hydraulic models have been suggested to correlate the hydraulic conductivity and hydrate saturation in sediments. Moreover, various numerical simulators have been developed to investigate the gas productivity in field production tests. The K-hydrate simulator was developed to analyze the potential of pilot production of gas hydrates in the Ulleung basin, East Sea, Korea. In this study, an empirical hydraulic model for the Ulleung basin was derived and applied to a simulator using the experimental results from disturbed field specimens. Production test simulations were performed considering the newly obtained hydraulic model, the depressurization method, and a production period of 14 days. The simulation results accurately represent the gas and water production rates over production time and vertical displacements in the vicinity of the production well.

Keywords. Methane hydrate, hydraulic model, thermal-hydraulic-mechanical simulation, productivity and stability analysis, depressurization method.

1. Introduction

Hydrates are a future energy resource that exist as ice crystals on the seafloor at low temperature and high pressure. Many hydrate bearing sediments (HBS) have been found around the world, and researchers have been actively evaluating the amount of gas hydrate in these reservoirs. The global estimation of methane hydrate in HBS ranges between 10^{14}–10^{16} m^3 STP [1]. The possibility of the presence of hydrate in the Ulleung Basin was suggested by KIGAM in 1996. The potential of methane hydrate was

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confirmed with the collected core data from three drilling sites [2]. The Ulleung Basin is estimated to have approximately 0.6 billion tons of hydrate gas, which could be used for 30 years by the whole nation [3].

Several methods for producing gas hydrate from the HBS have been suggested by previous researchers (e.g., depressurization, thermal/inhibitor injection methods). Depressurization is a method that produces gas hydrate by decreasing the pore pressure to a pressure equal to or lower than the phase equilibrium pressure of the hydrate. Korean researchers have selected the depressurization method as a production method for trial production tests in Ulleung Basin.

2. Model description

The section describes the modeling and constitutive hydraulic models. A detailed description of the development and verification of a thermal-hydraulic-mechanical (THM) simulator was presented in Kim et al. [4].

2.1. Constitutive hydraulic model

Permeability is a key parameter to evaluate the productivity of a gas hydrate. During depressurization, the effective stress increases with decreasing pore pressure. This leads to a settlement of HBS (i.e., decrease in pore space). For estimating the variation of effective stress in two-phase flow, Dangla model [5] which is function of each saturation and pore pressure (e.g., gas and water) is used in FLAC2D. Thus, a hydraulic model must be able to consider the variation of hydrate saturation.

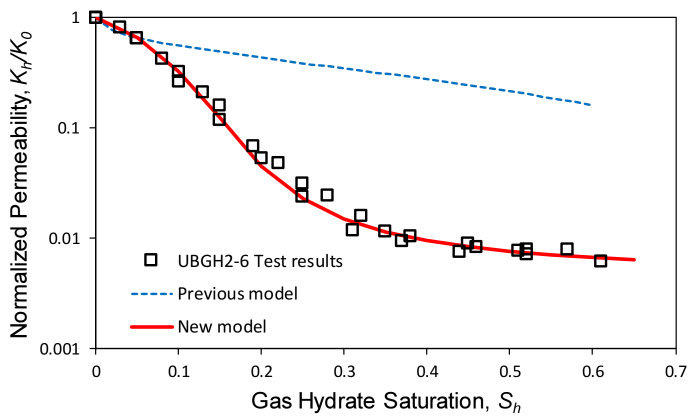


Figure 1. Comparison of hydraulic models.

The permeability tests were conducted using a specimen from the Ulleung Basin to gain an insight into the hydraulic characteristics. The relative permeability with hydrate saturation was normalized with the intrinsic permeability, which is the permeability at zero hydrate saturation. The normalized permeability is as shown in Figure 1. The results obtained using the Ulleung Basin specimen were lower than those obtained using the previous model (Eq. (1)). This means that the numerical analysis with previous model over-estimated the productivity of the gas hydrate. The constitutive hydraulic models are as shown in Eqs. (1) and (2). The proposed model is curve fitting model of permeability test using Ulleung Basin specimen.

$$\frac{K_h}{K_0} = \frac{(1-S_h)^{n+2}}{(1-S_h^{0.5})^2},\ n = 0.7S_h + 0.3\ \ [6], \tag{1}$$

$$\frac{K_h}{K_0} = A^{-\tan^{-1}(10S_h - B)+\frac{\pi}{2}} \cdot \frac{1}{K_{s0}},\ n = 0.7S_h + 0.3\ \ \text{(This study)}, \tag{2}$$

where, K_h is permeability with hydrate [-], K_0 is intrinsic permeability [-], S_h is the saturation of hydrate in HBS, and A and B are empirical constants (A=8.5, B=1.5).

2.2. Geometry and input parameters

The geometry for analysis is as shown in Figure 2. The input parameters were taken from Kim et al. (2018). The depressurization method was simulated for producing gas hydrate from the hydrate bearing sediment (HBS). Bottom hole pressures (BHP) were simulated as 3, 5, 7, 9, and 12 MPa for evaluating the effects of BHP on the productivity. The depressurization rate was 0.5 MPa/h and the trial production period was 14 days for all cases.

The constitutive hydraulic models mentioned in subsection 2.1 were applied for parametric analysis for evaluating the effects of both models on the productivity of gas hydrate and stability at the seafloor.

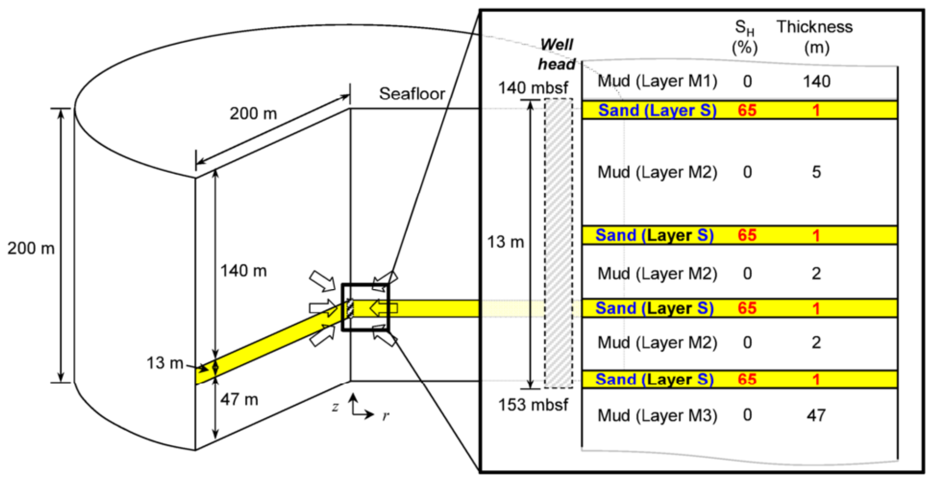


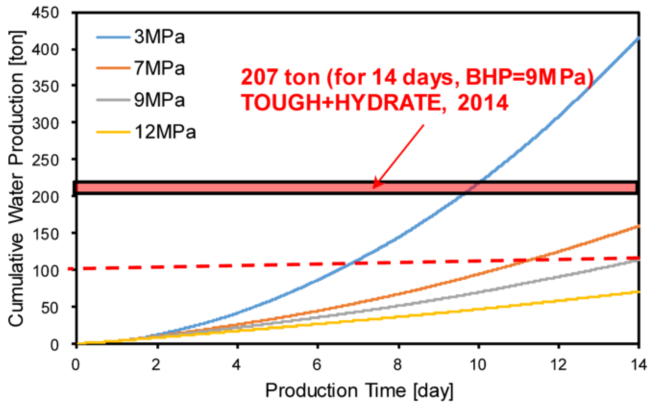
Figure 2. Geometry of analysis (Kim, 2015).

3. Results and Analysis

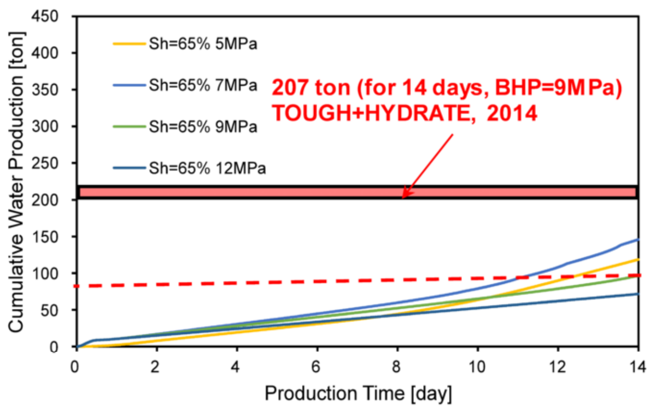
This section describes the results of numerical analysis and discusses the productivity and stability of the seafloor according to the hydraulic model. The results of productivity of gas and water, and the results of displacement at seafloor are presented in this section.

During the depressurization, a large amount of water is also discharged through the production line. Therefore, water production evaluation is also essential for accurate gas production measurement.

In addition, the HBS is settled by the increased effective stress during the depressurization, which has a considerable influence on the stability of the production well. Therefore, it is essential to evaluate the amount of settlement at the seafloor during the hydrate production.



(a) Results from the previous model



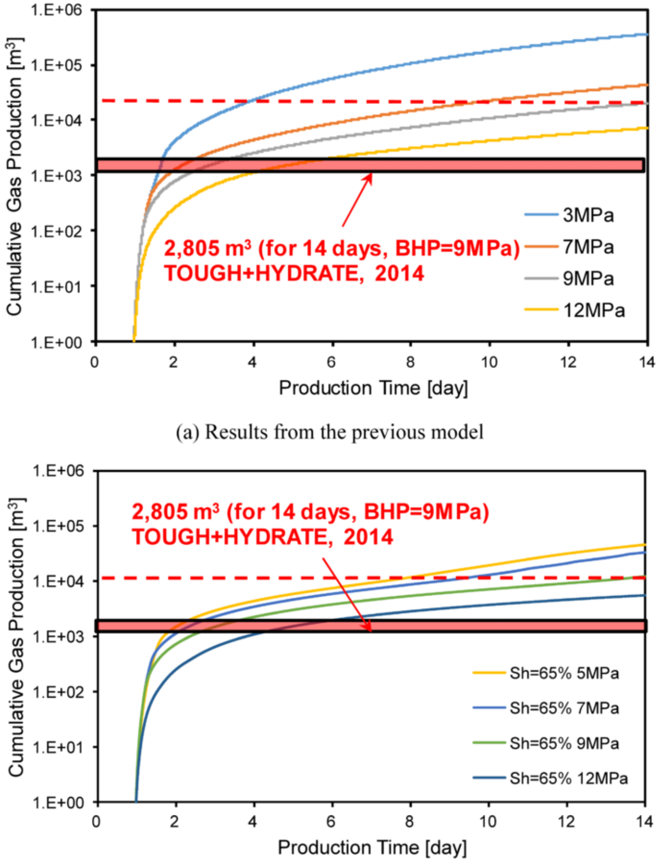
(b) Results from the developed model

Figure 3. Cumulative water production with production period.

3.1. Productivity of gas and water

The cumulative water production rate is as shown in Figure 3. As shown in Figure 1, the hydraulic model with saturation of gas hydrate in this study estimates a lower permeability compared to that by the previous model. Hence, the cumulative water production induced by the proposed model is also lower than that by the previous model. The amount of cumulative water production increases proportionally with BHP. In case of the previous model, approximately 100 tons of water is produced for 14 days after depressurization until the BHP is 9 MPa. On the contrary, the proposed model yields a cumulative water production of approximately 70 tons. However, both results are lower than the results of Mallik projects using the TOUGH HYDRATE simulator.

The cumulative gas production shows a similar trend as that of the cumulative water production, as shown in Figure 4. However, both the results involved a larger amount of cumulative gas production than that obtained by the Mallik case using the TOUGH HYDRATE simulator. These reverse trends are presumed to be due to the differences in the method of coupled simulation. TOUGH HYDRATE is a thermal-hydraulic (T-H) coupled simulator; the simulator developed herein is a thermal-hydraulic-mechanical (T-H-M) coupled simulator. During the depressurization, ground subsidence of HBS occurs due to the increasing effective stress. As shown in the above results, different coupling methods yield different results. Therefore, T-H-M analysis should be conducted to accurately simulate the behavior of HBS under depressurization.



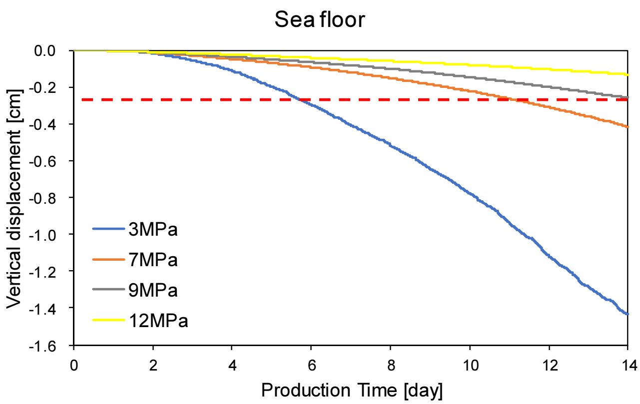
(a) Results from the previous model

(b) Results from the developed model

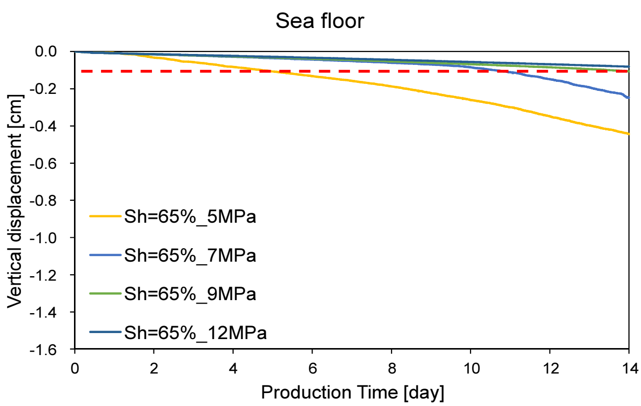
Figure 4. Comparison of hydraulic models.

3.2. Stability of the seafloor

Under the depressurization method, the subsidence of HBS occurs due to the increase in effective stress. The vertical displacements at the seafloor are shown in Figure 5. The analysis of the developed hydraulic model yielded lower subsidence of HBS than that obtained by the model defined in existing literature. The ground subsidence increased with decreasing BHP. The maximum vertical displacement at the seafloor was approximately 0.4 cm when the BHP was 3 MPa. The target BHP for a pilot test in the Ulleung Basin was 9 MPa. When the applied BHP was 9 MPa, the maximum vertical displacement was approximately 0.25 cm. Although the absolute displacement is small compared to the total thickness of HBS, the stability assessment of HBS is essential to prevent gas leakage and economic losses due to failure of the production well during gas production.



(a) Results from the previous model



(b) Results from the developed model

Figure 5. Displacement at seafloor under depressurization.

4. Conclusion

A hydraulic model for the Ulleung Basin is suggested through the permeability test using a specimen from the Ulleung Basin. A derived hydraulic model is applied to the T-H-M simulator. The productivity and ground stability of the testbed for the pilot production is carried out with the bottom hole pressure. The key findings of this study are as follows:

- The hydraulic model of the Ulleung Basin yields lower values than the previous literature model does.
- It is confirmed that the cumulative water production obtained from the proposed model is approximately 80 tons for 14 days, which is less than half of the water production of the Mallik pilot test.
- The cumulative gas production after 14 days from depressurization is approximately 10 times more than that of the Mallik pilot test.
- The differences in trends of the derived amount of gas and water are due to the differences in the considered constitutive model (i.e., T-H analysis (TOUGH HYDRATE) or T-H-M analysis (this study)).
- The ground subsidence derived from the proposed model is larger than that by the previous literature model because of the reduction in the water and gas production.
- T-H-M analysis should be conducted for accurately estimating the water and gas productivity and ground stability.

Acknowledgments

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